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AFGL-TR-87-0090

HIGH RESOLUTION ULTRAVIOLET FILTER DEVELOPMENT

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AIR FORCE GEOPHYSICS LABORATORY
Air Force Systems Command
United States Air Force
Hanscom Air Force Base, Massachusetts 01731

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"This technical report has been reviewed and is approved for publication"

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FOR THE COMMANDER

Division Director

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The SBIR Phase I research reported herein arose out of the AFGL interest in acquiring high-resolution images of missile plumes and similar phenomena, and the lack of ultraviolet filters of adequate resolution quality.

The task objectives were first to develop filter spectral designs capable of rejecting (to better than six to eight orders of magnitude) all visible radiation, providing a clear window below 4000A and down to as near 2000A as reasonably feasible, or such narrower band as needed, without degrading the resolution of the transmitted image by more than 5 line-pairs per mm, or the transmittance by more than three orders of magnitude.

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19. ABSTRACT (continued)

Next, to develop physical designs for a set of filters that meet the spectral and image quality requirements and that can be fitted to an existing AFGL ultraviolet camera system for evaluation and for subsequent field use. Finally, to fabricate a set of filters that realize the specific image quality and other performance requirements, and thereby demonstrate the feasibility of the approach for more general high-resolution ultraviolet imaging filter requirements.

The general methodology employed was to undertake a group of computer-assisted spectral designs, test these for suitability by fabricating test films in the production plant, realize the designs by fabricating a set of physical filters complying with the requirements and compatible with an existing AFGL ultraviolet imaging camera, and test the final filters for spectral and resolution performance.

A representative set of optical filters suitable for use in obtaining high-definition ultraviolet images with the existing AFGL telescopic camera was designed, and a set of filters was fabricated realizing the designs. The results show that the rejection of the filters in the visible was in each case better than eight orders of magnitude. The peak transmittance was 25 percent or better.

The inherent image definition capability of the filters themselves is estimated to be better than 40 line-pairs per mm. There should be no observable degradation in the imaging performance of the camera system for which they are intended, which has been estimated to be 15 to 20 line-pairs per mm.

The resulting filter set performance exceeds the target objectives set down at the outset. We conclude that the successful accomplishment of the Phase I objectives has demonstrated the feasibility of developing a more general design and manufacturing capability that will provide high-resolution ultraviolet filters readily and reliably.

The implications of the successful Phase I effort are that furtherance of the research by a Phase II program is justified and should be undertaken. The Phase II program should generalize the Phase I objectives, encompassing the ability to produce filters for imaging requirements down into the vacuum UV (1200A) and including both narrow-band and wide-band filters. Filter design methods need to be explored in greater depth, including computer design methods, materials, alternative deposition technologies, deposition monitoring techniques, process parameters, spectral and resolution testing technology, and manufacturing producibility.

The final filter set produced was delivered to the sponsoring activity, AFGL, together with performance data, to allow evaluation in a representative camera system and subsequent field use if desired.

The pursuit of a follow-on Phase II program is expected to benefit applications for high-resolution image capability in rocket research, propulsion research, aurora and airglow research, space exploration, solar studies, defense, and scientific development. The availability of such filters is expected to trigger innovation and create new needs for both government and high-technology commercial applications.

Summary

• The research reported herein is addressed to the development of a design and manufacturing technology for producing high resolution ultraviolet light filters, needed for the acquisition of high definition images in the ultraviolet of missile plumes and similar phenomena where an object is emitting or is illuminated by ultraviolet light.

For Phase I, the task objectives were to:

1. Develop filter spectral designs capable of rejecting (to better than six to eight orders of magnitude) all visible radiation, providing a clear window below 4000A and down to as near 2000A as reasonably feasible, or such narrower band as needed, without degrading the resolution of the transmitted image by more than 5 line-pairs per mm, or the transmittance by more than three orders of magnitude.

2. Develop physical designs for a set of filters that embody the desired spectral designs and image quality requirements and that are compatible with specified mechanical constraints, so that they can be employed in an existing AFGL ultraviolet camera system for evaluation and for subsequent field use.

3. Fabricate a set of filters that realize the specific image quality and other performance requirements, and thereby demonstrate the feasibility of the approach for more general high-resolution ultraviolet imaging filter requirements.

The technical problems included:

1. Development of spectral filter designs making use of all available filter techniques to achieve the simplest suitable design with the fewest components. Selection of designs that give adherent, durable stable and reproducible films.

2. Ensuring that light scattering from interference films is minimal to avoid both increased background and unacceptable degradation of image quality.

3. Maintenance of interactive reflectances between interface surfaces sufficiently low to assure the image quality sought.

4. Specification of substrates of adequate optical quality to assure the image quality sought.

5. Review of the camera optical system to assure a suitable location for interposing filters, and to estimate the effects upon focus shift and aberration.

6. Evaluation of film designs by experimental fabrication and measurement.

7. Development of a suitable resolution test bench to allow evaluation of the image degradation characteristics of filters.

8. Realization of the filter designs developed, to permit evaluation of the theoretical designs.

The general methodology employed was to undertake a group of computer-assisted spectral designs, test these for suitability by fabricating test films in the production plant, realize the designs by fabricating a set of physical filters complying with the requirements and compatible with an existing AFGL ultraviolet imaging camera, and test the final filters for spectral and resolution performance.

A representative set of optical filters suitable for use in obtaining high-definition ultraviolet images with the existing AFGL telescopic camera was designed, and a set of filters was fabricated realizing the designs. The results show that the rejection of the filters in the visible was in each case better than eight orders of magnitude. The peak transmittance was 25 percent or better.

The inherent image definition capability of the filters themselves is estimated to be better than 40 line-pairs per mm. There should be no observable degradation in the imaging performance of the camera system for which they are intended, which has been estimated to be 15 to 20 line-pairs per mm.

The resulting filter set performance exceeds the target objectives set down at the outset. We conclude that the successful accomplishment of the Phase I objectives has demonstrated the feasibility of developing a more general design and manufacturing capability that will provide high-resolution ultraviolet filters readily and reliably.

The implications of the successful Phase I effort are that furtherance of the research by a Phase II program is justified and should be undertaken. The Phase II program should generalize the Phase I objectives, encompassing the ability to produce filters for imaging requirements down into the vacuum UV (1200A) and including both narrow-band and wide-band filters. Filter design methods need to be explored in greater depth, including computer design methods, materials, alternative deposition technologies, deposition monitoring techniques, process parameters, spectral and resolution testing technology, and manufacturing producibility.

The final filter set produced was delivered to the sponsoring activity, AFGL, together with performance data, to allow evaluation in a representative camera system and subsequent field use if desired.

In order to measure the resolution of the filters, it was necessary to assemble a test bench. This was intended only for the immediate purpose, but illustrated the critical factors and emphasized the need for a more appropriate test facility in connection with a continuing Phase II program.

The pursuit of a follow-on Phase II program is expected to benefit applications for high-resolution image capability in rocket research, propulsion research, aurora and airglow research, space exploration, solar studies, defense, and scientific development. The availability of such filters is expected to trigger innovation and create new needs for both government and high-technology commercial applications.

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1. Introduction

This document is the final report of a Small Business Innovative Research Project, investigating Topic AF86-72 under the sponsorship of Air Force Geophysics Research Laboratory, Hanscom Air Force Base, Bedford, Massachusetts. The topic arose out of the interest of AFGL in obtaining high resolution ultraviolet images, particularly of missile plumes, and the consequent need for optical filters of high imaging quality that would not degrade the resolution of the camera systems used. A principal purpose of such filters is to eliminate (reject) visible and longer wavelength radiations so that they do not reach the imaging plane. While presently available filters can reject undesirable radiation to a sufficient degree, their transmittance is typically low and the image resolution of the present camera system when using such filters has been inadequate and significantly poorer than the basic camera system without the filters.

The need, therefore, is for the development of a design and manufacturing technology that can produce high resolution ultraviolet filters that meet the performance requirements sought and enable the acquisition of high quality images in the ultraviolet, furthering the research mission of AFGL. The specific objective of this Phase I project was to design and fabricate a set of ultraviolet filters for an existing AFGL camera that would significantly improve its resolution capability for ultraviolet images, and thereby also demonstrate the feasibility of developing a more general technology that would enable the production of the several different types of filters, with various spectral range requirements, that are useful in ultraviolet imaging applications.

While the most immediate interest is in the study of rocket plumes using ground-based camera systems, it should be evident that in-flight systems carried by shuttle, balloon or rocket will find applications for such high-resolution image capability for rocket research, propulsion research, aurora and airglow research, space exploration, and many defense applications, both classified and unclassified.

In this Phase I project, we have, in conjunction with the sponsor, identified a specific near-term need and using generally applicable principles developed several designs for a suitable set of ultraviolet filters. Ability to fabricate the necessary films has been evaluated by endeavoring to produce such films using representative production equipment, and then testing the resulting films. The most suitable of these films were evaluated exhaustively and then fabricated into a set of filters capable of incorporation into an AFGL camera for further evaluation in the field. At this point the spectral characteristics of the filters, including particularly the important rejection in the visible, were considered satisfactory.

It was next necessary to evaluate the resolution or image quality of the filters, which can only be done in the context of a reference system in which the filter is deployed. The expectation at the outset of the project was that an appropriate camera system for testing the resolution of any films or filters produced would be available at AFGL, and in fact it was expected that an image analysis system for accurately evaluating the camera test images would also be available, which could simplify and enhance the evaluation process. As it turned out, AFGL field investigation schedules preempted the equipment proposed to help with our evaluations and we found it necessary to undertake the resolution testing in our own laboratories at MicroCoatings. This proved an unexpected blessing, as it helped us appreciate the necessity of such testing, and the experimental obstacles to achieving the desired level of resolution and to obtaining suitable documentation of the test measurements.

The results of resolution testing are detailed in Section 7 of the report. The main conclusion is that the filters produced are sufficiently good that they produce no noticeable degradation in the imaging quality of the camera system in which they are intended to be used, which has been estimated to be capable of 15 to 20 line-pairs per millimeter. There is evidence to suggest that these filters are capable of substantially better performance (40 to 50 line-pairs per mm), but this cannot be demonstrated with the present camera system.

The performance of the filter set produced is considered to be highly satisfactory, and to comply fully with the performance objectives targeted at the outset of the project. More broadly, the results of the project are considered to demonstrate entirely adequately the feasibility of developing a design and manufacturing capability that will provide high-resolution ultraviolet filters readily and reliably.

In the final sections of the report we discuss questions that should be addressed in the Phase II continuation of this program, specific filter applications that have already been identified as of considerable and timely interest, and the steps necessary to bring the technology to the point where implementation of production in Phase III can be confidently undertaken with respectable yields and economy of production. We also discuss other applications for the technology, the recognition of new applications and generation of demand, and the impact of such innovation upon creating new perceptions of need, application and demand.

2. Definition of the Problem

The basic objective in simplest terms is to be able to obtain and record high quality images of an object that is emitting or is illuminated by ultraviolet light. In the context of relevance to Air Force Geophysics Laboratory, this broad definition can be limited in the following respects:

1. Ultraviolet light is here regarded as the region of the spectrum below 4000A. Most user activity in the region is concentrated between 2000-4000A, but there is also interest in the vacuum ultraviolet (VUV), particularly in H 1216 (Lyman-alpha), O 1304, O 1356, and the N_2 LBH bands.

2. What constitutes high image quality varies depending upon the specific application, but for our immediate purposes good image definition means at least the ability to clearly resolve 15 line-pairs per mm. In the longer view, we wish to be able to resolve upwards of 30 line-pairs/mm, perhaps even up to 50 line-pairs/mm.

3. The object to be photographed may be at relatively close range (say, less than ten meters), but ordinarily will be at distances measured in kilometers, and commonly well above the earth's surface.

4. The camera obtaining the image may be ground-mounted, but in more advanced studies is likely to be carried on board a balloon, rocket, or space shuttle.

5. In almost every instance, the radiation entering the camera will include not only the ultraviolet from the object, but also visible and infrared radiation from the object, from the sun, and from other interfering sources that need to be discriminated against, so that the camera records only the image of interest.

How we happened to get to this point is relevant. AFGL has for many years been working on upper atmosphere research [Reference 1] and on photographic imaging, but only recently has high quality ultraviolet imaging received important emphasis as a research technique [Reference 2]. Attempts to use commercially available interference filters in an ultraviolet camera gave very unsatisfactory results -- resolution poorer than five line-pairs per mm in a camera system capable of better than 15 lp/mm. The available filters became the system limiting component, and in fact could ordinarily not be used when making important measurements. This situation lead to a specific set of filter characteristic requirements, which will be described in the next section (Phase I Objectives).

We have discussed the system requirements, and what constraints are thereby imposed on the filters used in such a camera system. From this we can devolve the issues that need to be addressed in designing and fabricating filters suitable for the application. In general terms, one needs to:

1. Use substrates of adequate optical quality (concern for inclusions, striae, index uniformity, wedge, surface regularity, surface finish, etc.) to assure the image quality sought.

2. Maintain interactive reflectances between interface surfaces (coated or uncoated) sufficiently low to assure the image quality sought.

3. Review the camera optical system design to determine the most suitable location for interposing filters. Analyze to find the effects on focus shift and increased aberration, and determine what optical corrections, if any, need be made.

4. Assure that light scattering from interference films is minimal to avoid both increased background and unacceptable degradation of the image quality.

5. Choose interference film designs that are relatively insensitive to normal variations in deposited film thickness, so that resulting film spectra are reasonably reproducible. Choose designs that give adherent, durable and stable films.

6. Take advantage of all available filter techniques (all-dielectric film, metal-dielectric film structures, absorbing materials, etc.) to achieve the simplest suitable design with the fewest components.

Finally, these considerations have to be combined in a unified design, fabrication, and testing methodology. We cannot, in Phase I, expect to accomplish all this for the wide diversity of ultraviolet applications. The reasonable objective we have set is to carry out the design process for a few representative requirements of current usefulness, and demonstrate feasibility by realizing and testing such filters, proving that expected performance can be achieved. The Phase I objectives are set forth in the next section.

3. Phase I Objectives

In undertaking the development of high-resolution filter technology, it was fortuitous that certain short-term requirements of AFGL could readily be incorporated as objectives of the development. These requirements were as follows:

1. Common to almost all ultraviolet imaging situations is the need to be totally free of all visible and infrared radiation, and ideally to provide a clear window below 4000A and down to as near 2000A as reasonably feasible. In this instance, the need was for such a filter capable of being incorporated in an existing ground-based camera system [see Figure 1] employing a 200-mm focal length Cassegrainian reflective telescope. This filter was given the label FILTER B.

   Mechanically, Filter B was intended to be mounted in a rotating filter wheel holder, located just behind the telescope and just ahead of a UV-sensitive photocathode. Electrons from the photocathode are accelerated by a microchannel plate, impacting on an image intensifier tube, and producing a visible display. The filter was to be nominally 25 mm diameter. Because the response of the photocathode is essentially dead above 6000A, the rejection zone required covered the range from 4000 to 6000A. It was necessary however to reject* such visible light by six to eight orders of magnitude, or even better if possible. Figure 2 diagrams the spectral response objectives for Filter B.

2. A second filter was required, to provide all of the visible rejection of Filter B, but having the UV transmission band narrowed to the region 2000 to 3000A. Rejection of the upper UV was not as stringent as for the visible, but three to five orders of magnitude were sought. This filter was designated FILTER AB. The mechanical and positioning aspects were the same as for Filter B. The spectral response objectives for Filter AB are diagrammed in Figure 3.

3. There still remained a requirement to be able to transmit the full unfiltered spectrum when desired. Since the physical thickness of filters B and AB was expected to be significant (best estimates ca. 10 mm) the change in optical path length and its defocussing effect had to be recognized. To deal with this it was decided to make all filters as nearly the same optical pathlength as possible, providing a similar element of clear fused silica for use when examining the unfiltered spectrum. This pathlength equalizer was designated Filter Q.
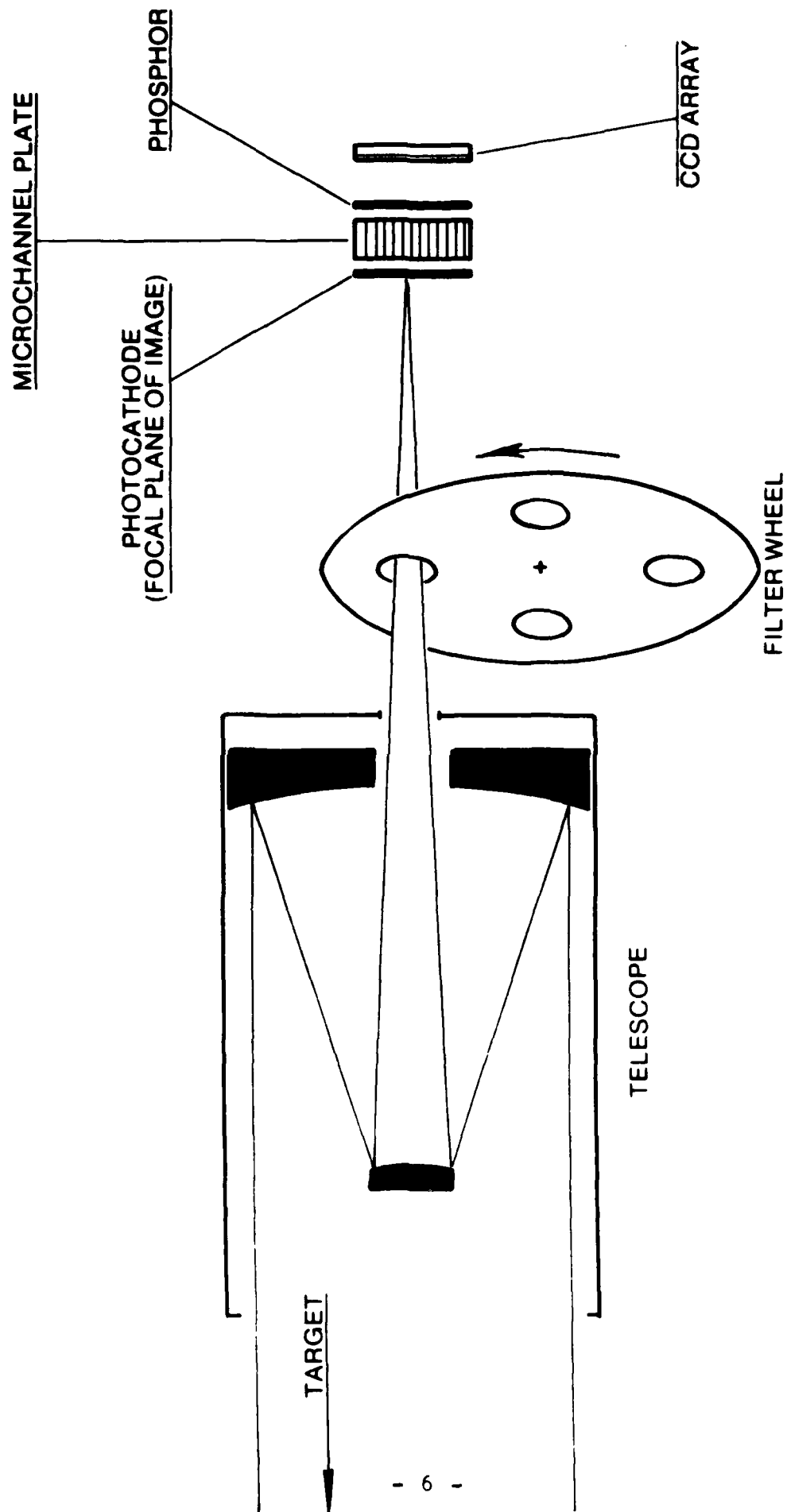
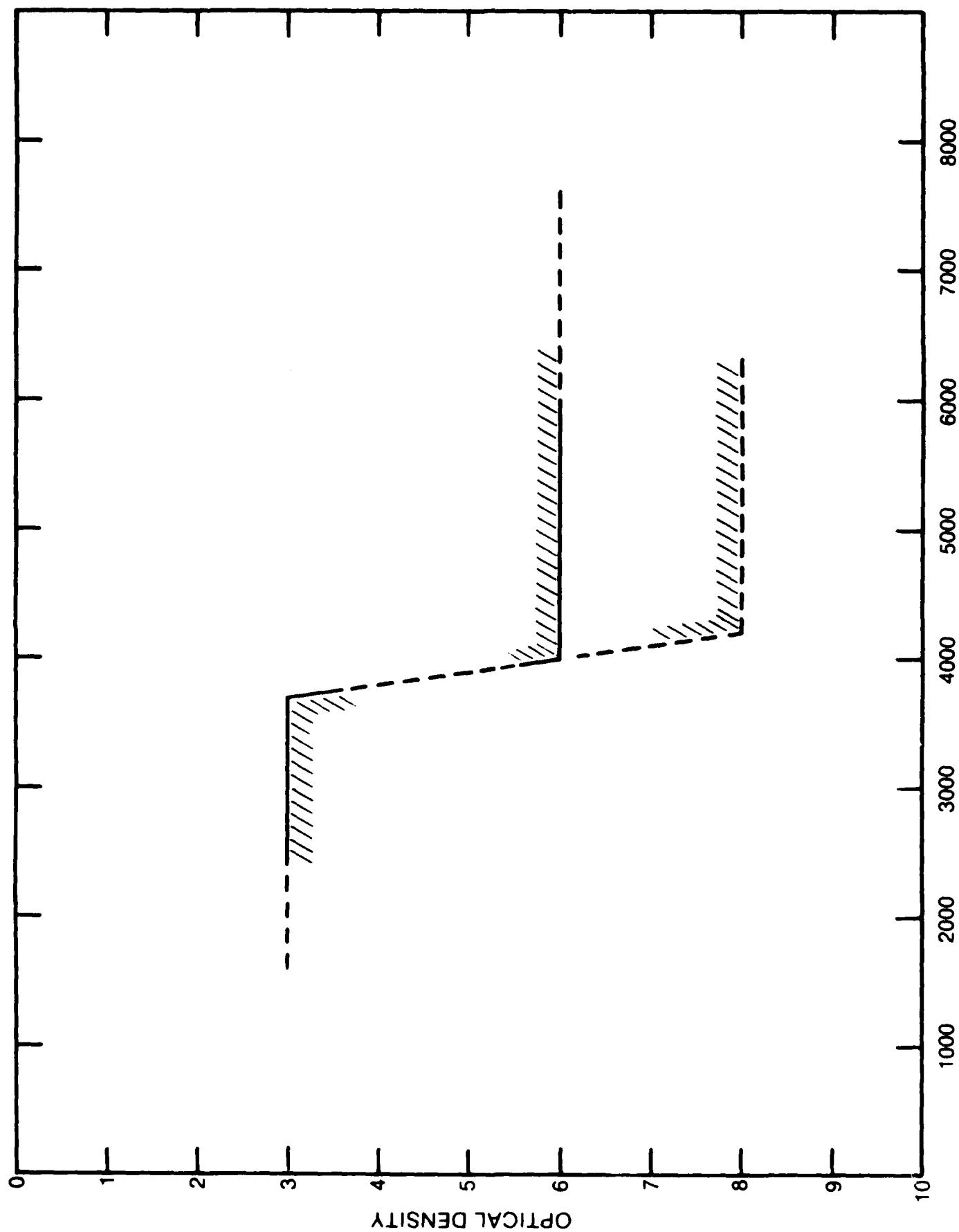Figure 1. AFGL Ultraviolet Imaging Camera
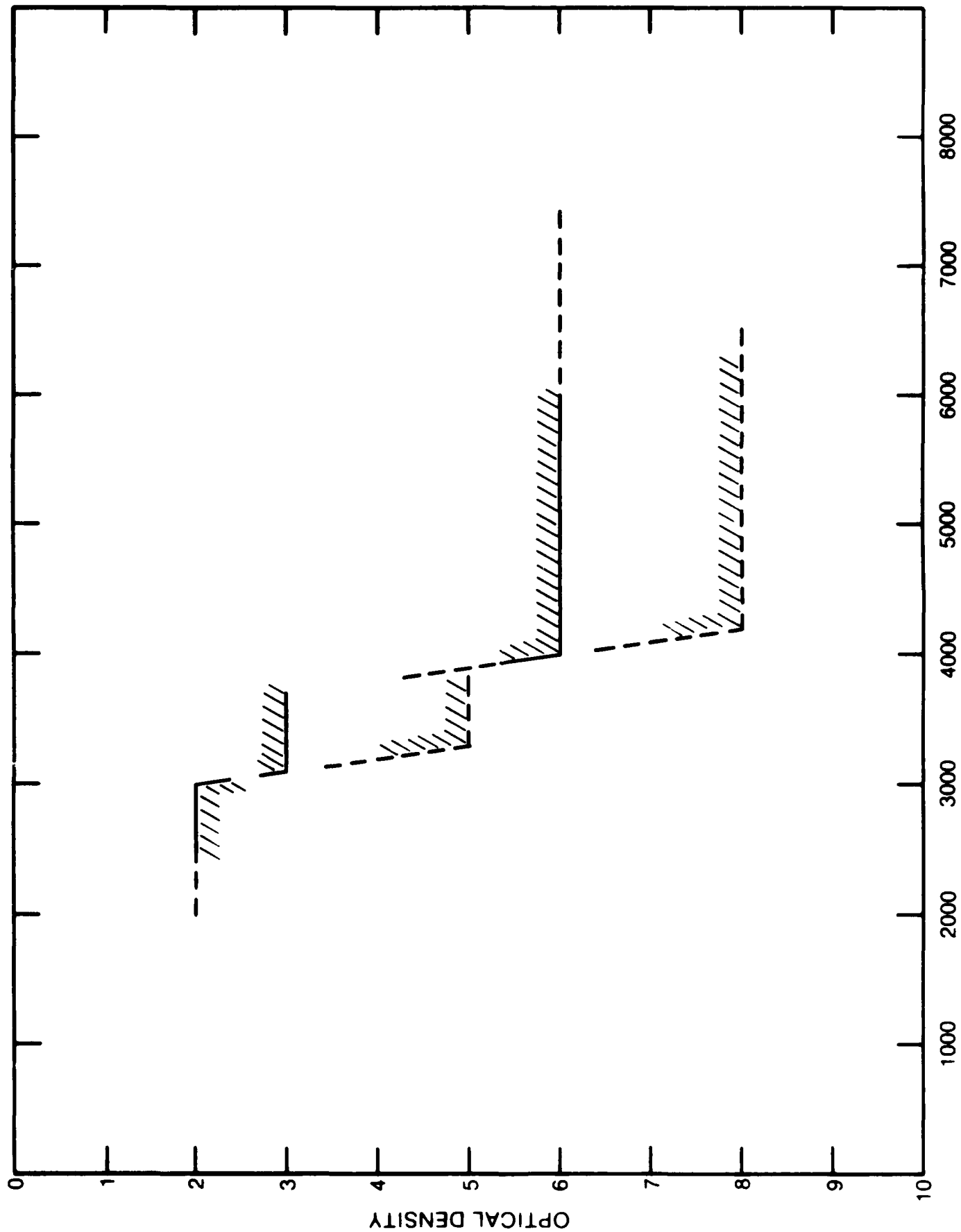
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Figure 2. Spectral Response Objectives – Filter B

Figure 3. Spectral Response Objectives – Filter AB

OPTICAL DENSITY

WAVELENGTH. ANGSTROMS

The Phase I objectives were therefore established as follows:

1. Develop computer-assisted filter designs that spectrally satisfy the above requirements.

2. Develop physical designs of filters that embody the desired spectral designs and performance characteristics and that are compatible with the mechanical constraints so that they can be employed in the existing camera system.

3. Fabricate a set of filters that realize the specific image quality and other performance requirements, and thereby demonstrate the feasibility of the approach for more general high-resolution ultraviolet imaging filter requirements.

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*NOTE: The concept of _rejection_ of light deserves elaboration. In the present context it means the extent to which an optical transmission filter reduces the intensity of light (generally within a specified wavelength interval) incident on its face to that transmitted through the filter, and is normally used only in discussing spectral intervals where minimal or zero transmittance is desired. It is thus the transmittance of the filter in a spectral region where it is desired that the filter transmit poorly or ideally not at all. For very small values of transmittance, rejection is more conveniently specified in logarithmic units or in orders of magnitude. The term "blocking" is used synonymously with "rejection" by optical filter designers, and is the more common jargon. Blocking (or rejection) includes both back-reflection of incident light and absorption by lossy materials of which the filter may be made. One must therefore be cautious in using the term attenuation to discuss the situation: the incident beam intensity is attenuated by the transmittance value of the filter, but only part of this attenuation may be the consequence of absorption.

4. Theoretical Development

Examination of the requirement of Filter B to transmit an interval from near 2000A to as close to 4000A as possible using exploratory computer designs showed that this is too wide a band to allow using a metal-dielectric film. So, the absorption glass approach was used and optimized to achieve eight decades of blocking from 4700 to 6700A. This only partially fulfilled the requirement; blocking from 4000 to 4700A was insufficient. Therefore, all-dielectric filters were computer-designed to provide the additional blocking needed in this region when used together with a shortpass filter. Standard MicroCoatings design techniques were adapted to the present requirement. Confirmation of specific filter designs was then undertaken by fabricating experimental filters for evaluation.

The first experimental filter made was excellent in the blocking range (above 4000A), but the transmission interval, from 2500 to 3600A, was judged inadequate for AFGL purposes. In order to enlarge the tranmission interval, alternative designs were first computed but most did not look attractive. Deposition trials were made for one such approach, but the film did not possess an adequate transmission zone at the low wavelength portion of the spectrum. Different coating materials were then selected to sharpen the steepness of the transition zone. This approach worked out well and expanded the transmission interval to 2400-3825A, which was considered acceptable. This method was used to produce the final Filter B.

Filter AB requires a somewhat narrower transmission int   , 2000 (2400) to 3000A. Working with all-dielectric film oe   s requires a large number of layers, and this leads to sensit   ty to layer thickness errors and to rough bandpass spectral s' (i.e., having high ripple content). Consequently, metal-dielectric layer structures were computed to achieve the desired filter properties. The resulting bandpass filter has only moderate blocking in the 3000-4000A range, and so an all-dielectric blocker was investigated for use as an auxiliary filter. The computer-generated design required a fairly large number of layers to achieve the necessary blocking. The filter was made and approximated the design closely in the blocking zone, although the transmission zone was not as smooth as desired. The overall filter characteristics were deemed to be acceptable.

5. Experimental

To verify the computer designs and to ascertain the relative practicality of such designs in terms of reproducibility, film adherence, acceptable stress values within the films, film durability, etc., each design showing promise of usefulness was fabricated in the laboratory and tested against expectations. Based on these initial results, the number of layers and spectral locations were varied to produce a reasonable Filter B design.

It took a number of deposition trials to produce a filter with the critical features at the desired wavelengths. We monitored the deposition at wavelengths that were poorly transmitted by the absorption glass substrate being coated, so the deposition was monitored using a clear glass disk. This allowed the coating technician to deposit enough layers to achieve the blocking objectives.

The first of the Filter B designs fabricated showed too narrow a transmission interval. When the decision to use a different set of coating materials was made, new trials were required to determine the proper monitoring procedure and optimal deposition conditions. The successful filter required a number of attempts at manufacture. It was difficult to achieve a fast transition from the high transmission region to the blocking region. The exact conditions of deposition need more control than we attained in this particular production equipment if quantities of such an item are to be produced.

The AB filter was extremely difficult to monitor with the installed optical monitoring system. A number of deposition trials were made, and the best filter of the lot selected for the purpose. The auxiliary filter produced was not as ripple-free as we would have liked, but was adequate for the intended purpose (image quality evaluation). Filters with more regular spectral characteristics could be made with reasonable effort. The resulting AB filter had relatively low transmittance (ca.17%) and so an antireflection coating was added to bring the transmittance up to 25%. This will also reduce flair images, and should be routinely incorporated in subsequent construction.

6. Test Methodology

Testing of filters for this project involves evaluating several different measures of performance:

1. Transmission of desired spectral radiation

2. Rejection of undesired spectral radiation

3. Maintenance of image quality in system application

To measure transmittance, we used a Cary-Varian model 14 recording spectrophotometer, which has exceptionally good capability in the ultraviolet region of immediate interest. This is an established method with a proven and accepted instrument, and needs no further discussion.

Measurement of rejection is in principle the same as measuring transmittance, except that we need to measure very small values of transmittance, in this instance down to (exp)-12. The Cary 14 is one of the best instruments for this purpose, however it is still limited (by signal-to-noise) to a range of five decades, perhaps six. Ordinarily, such measurements are made by interposing a known neutral density filter in the reference beam of this double-beam instrument and then correcting the instrument indication accordingly. In the present case, where we are trying to measure as much as twelve decades of rejection, the dynamic photometric range of the instrument would thus appear to be insufficient. We are fortunate, however, in that the filters to be measured consist of several components stacked together, and it is possible to measure each component individually before final assembly. With judicious care, the individual results can be combined to produce the transmittance curve of the total assembly with a very high degree of confidence.

Measurement of system resolution, or tendency of the filter component to degrade the image quality, is a different technology entirely. Here, we have to assemble an optical test bench comprising at least a test target, an illuminating system (ultraviolet), a telescope to focus the image on a plane capable of responding to ultraviolet radiation, and eventually a method of recording the image. It is important that the optical bench be a reasonable approximation to the optical system (camera) in which the filter is to be employed, and that the filter under test be interposed in the test bench beam in nearly the same relative location as in the real application.

The quality of the focussing optics (wavefront distortion, surface cosmetics) must be high enough that the imaging of the system without the test filter is of adequate resolution to permit the desired level of performance measurement. A discussion of these requirements is given in Appendix A.

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We started to develop a test bench using a 2-inch diameter spherical mirror which we procured with the understanding that it was adequate (lambda/10) for our need. The test bench configuration (Layout I) is shown in Figure 4. The test target is a standard Air Force test pattern, as shown in Figure 5. Illumination from a Hg-arc is by transmission. The image is received on a phosphor screen at the focal plane, converting the UV image to a visible one [Figure 6]. In using this bench, we learned quickly that the use of a microscope to examine the visible image is awkward and inconvenient, but necessary since the unaided eye can resolve little better than two line-pairs per mm, and we were looking for better than 25 lp/mm. We also learned that secondary images can result from almost any unanticipated anomaly in the optics, and such superposed images prohibit seeing the resolution level sought.

In consequence, we took a new approach, using Layout II [see Figure 7]. This was based on a 1000-mm focal length ultraviolet Cassegrain telescope recently acquired by AFGL in order to upgrade the camera system for which the filters that we have produced are also intended. (Upgrading the camera system does not affect the filter requirements set forth in Section 3 above; the filter set produced should be equally suitable for the modified camera). As shown in Figures 7 and 8, we illuminated the test target from the front (to minimize secondary reflections) and using the telescope in reverse in an axial configuration projected the image some eight meters to a phosphor screen as before. The image is now enlarged about five times, instead of 1:1 as before. This is a legitimate procedure since the geometry of the telescope, filter and test target is very nearly the same as that of the telescope, filter and photocathode in the real camera application, only the direction of light travel is reversed. The enlargement of the projected image is a significant convenience, although focussing must be carefully attended to. This configuration also allowed us to position a conventional press camera (sans glass optics, but with shutter intact) at the image location. Using a polaroid filmpack (UV-sensitive) and holder allowed us to record the image for later examination under a microscope. There is some spherical aberration evident, but not enough to interfere with acquiring the necessary data. This system lacked grandeur, but made up for it in results, which were entirely adequate to prove performance to the necessary degree.

For each measurement the filter to be tested was placed in position on the test bench, approximately seven inches from the test target and about one and one-half inches in front of the end plate of the telescope [see Figure 9]. The same filter location was maintained for each of the tests. This position was chosen as being as nearly representative as possible of the geometry of the camera for which the filters are intended. With the filter in position, several trials were made to locate the camera film plane so that the best focussed image was obtained for that filter. The results of testing are detailed in the following section.
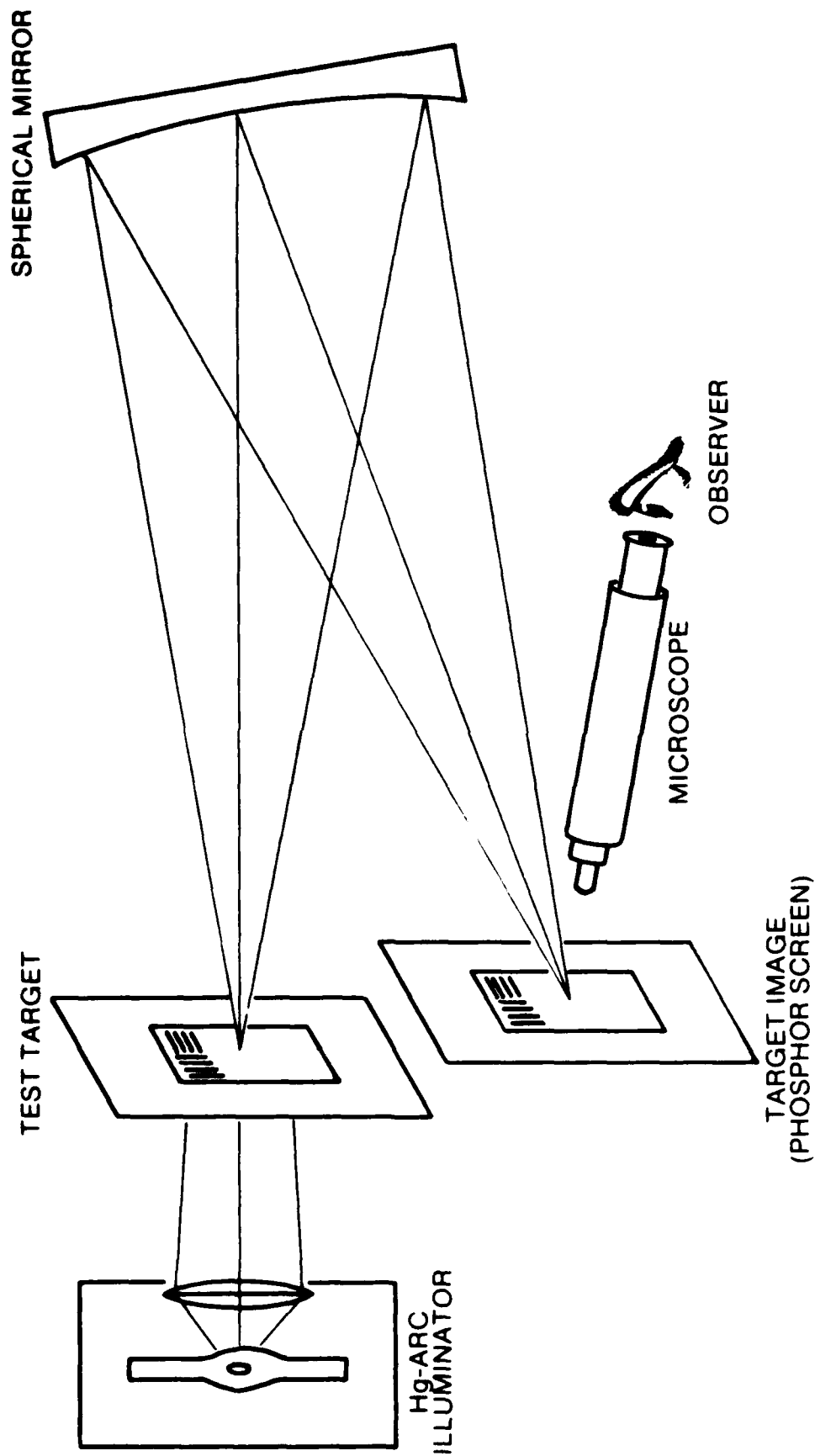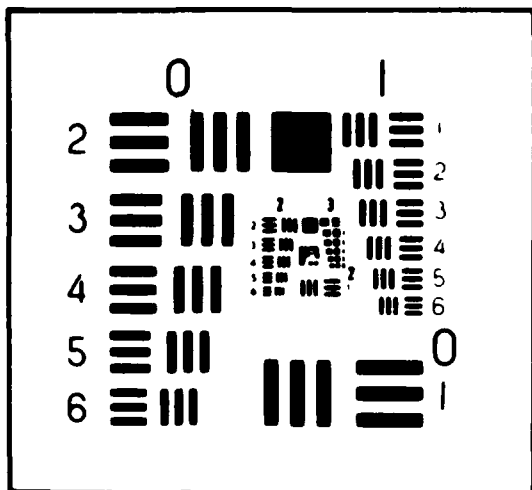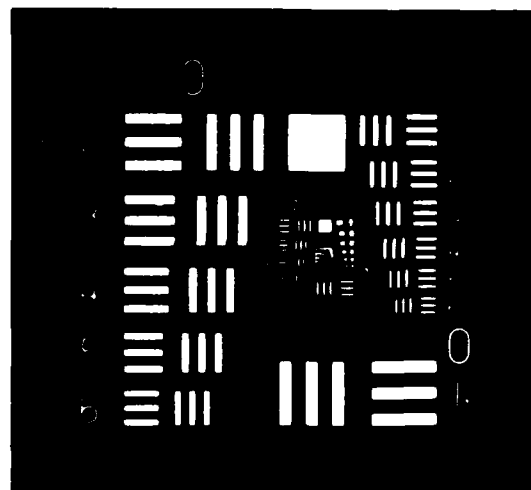
Figure 4. Test Bench Configuration - Layout I

Positive   Negative

Line Pairs Per Millimeter

Element	Group Number							
Number	0	1	2	3	4	5	6	7
1	1.00	2.00	4.00	8.00	16.0	32.0	64.0	128
2	1.12	2.24	4.49	8.98	17.95	36.0	71.8	144
3	1.26	2.52	5.04	10.1	20.16	40.3	80.6	161
4	1.41	2.83	5.66	11.3	22.62	45.3	90.5	181
5	1.59	3.17	6.35	12.7	25.39	50.8	102	203
6	1.78	3.56	7.13	14.3	28.51	57.0	114	228

Figure 5.   Resolution Test Target (USAF)

Figure 6. Typical Image of Resolution Test Target

PHOSPHOR SCREEN
(OR FILM PACK)

TARGET IMAGE

Hg-ARC
ILLUMINATOR

TELESCOPE

FILTER
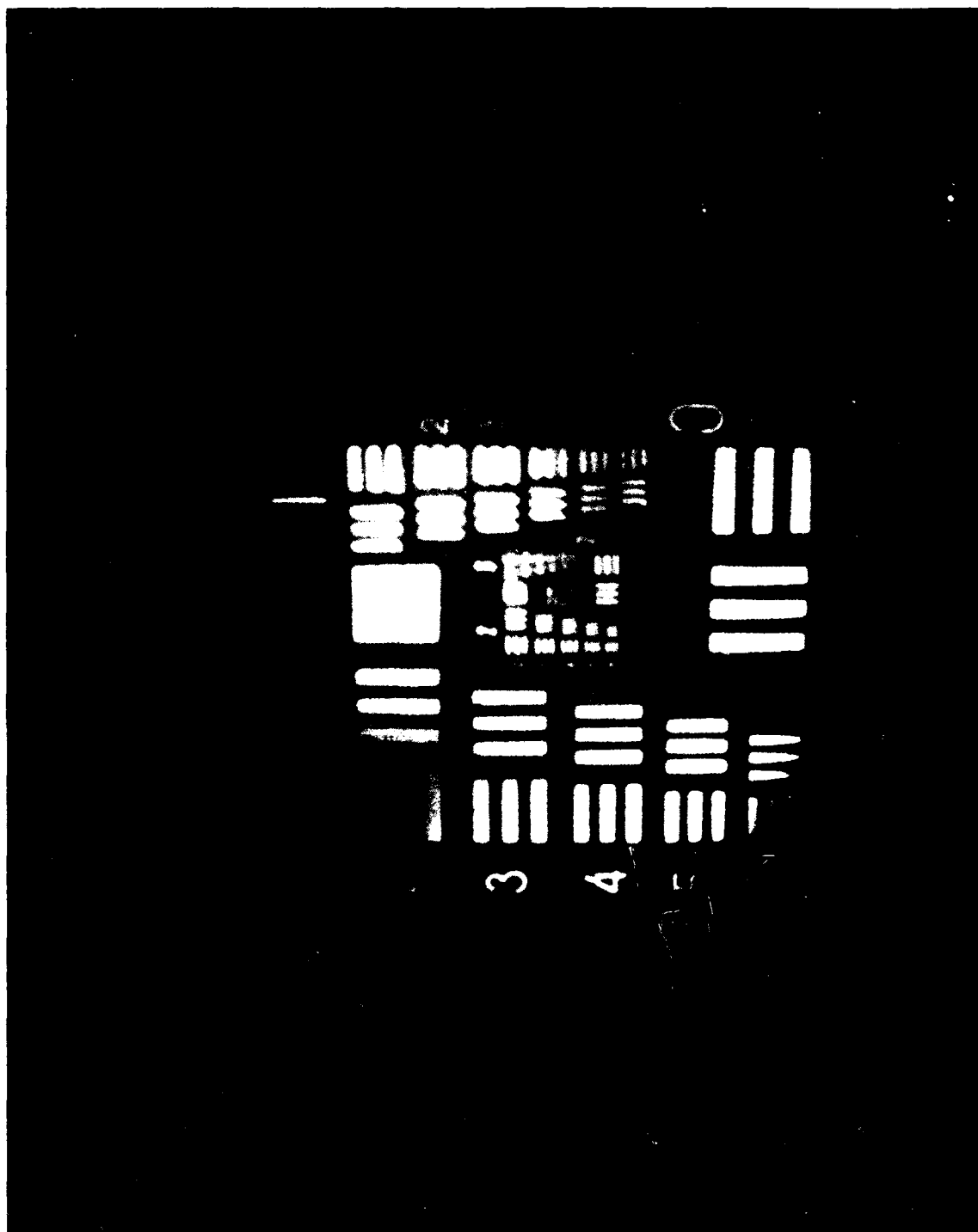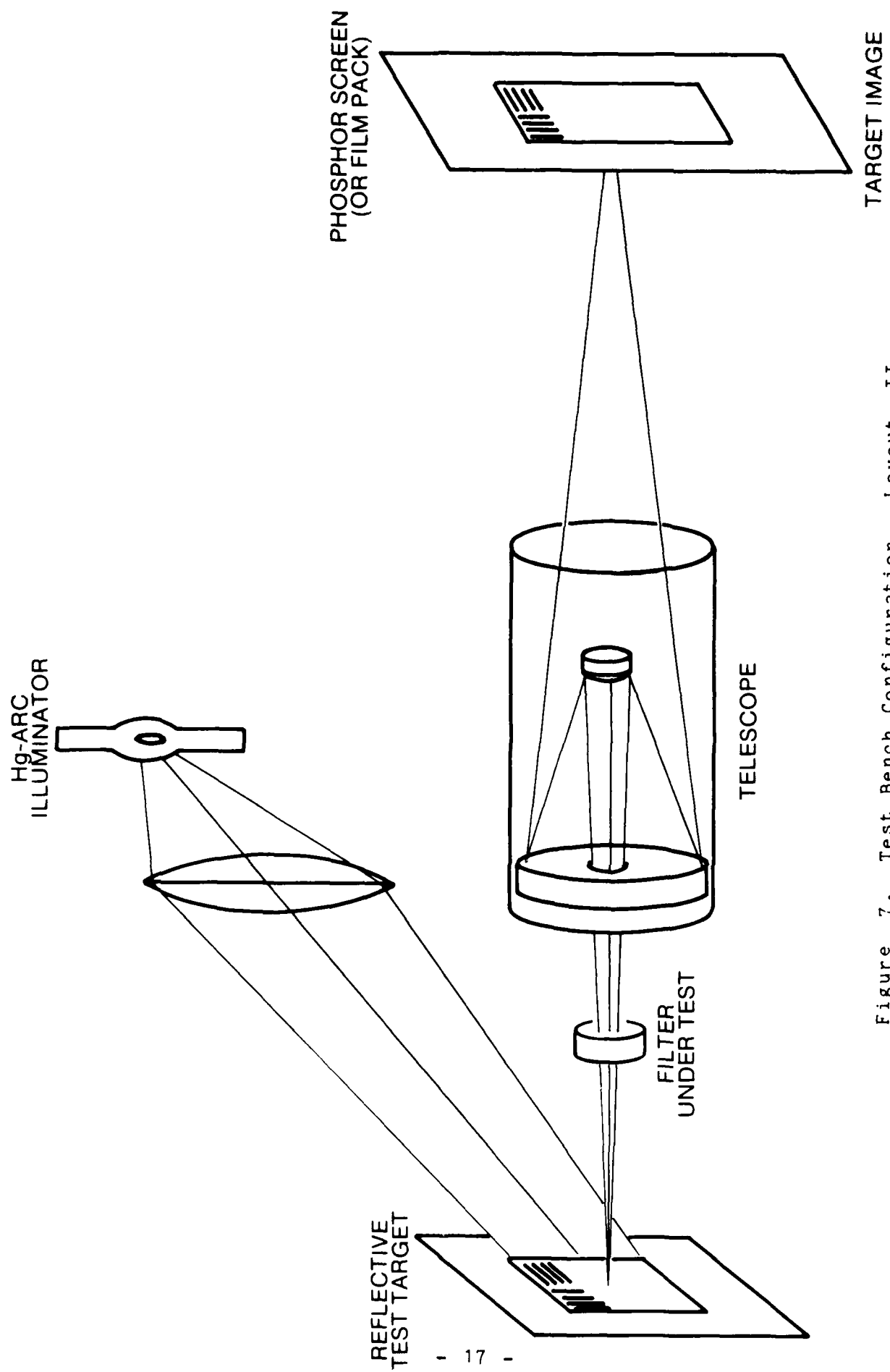UNDER TEST

REFLECTIVE
TEST TARGET

Figure 7. Test Bench Configuration - Layout II

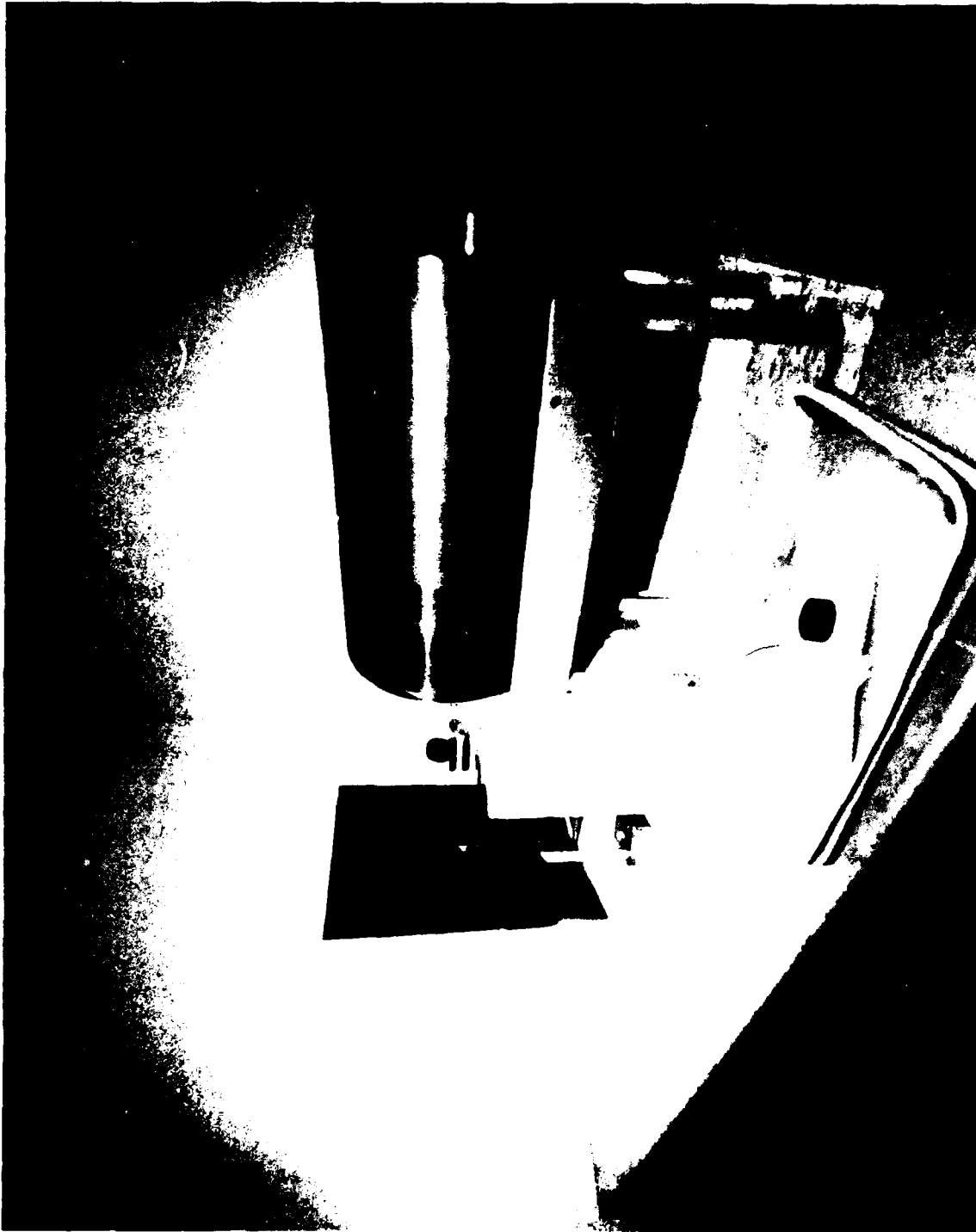Figure 8. _Test Bench - Layout II_

Figure 9. Test Bench - Filter in Test Position

7. Test Results

Using the methodology of the previous section, the filter set fabricated to demonstrate the feasibility of the technology was tested with the following results:

Spectral Performance

The transmittance of Filter B is shown on a logarithmic scale in Figure 10, and on a linear scale in Figure 11. The transmission band is basically from 2400 to 3825A. The peak transmittance is approximately 75 percent.

The visible rejection capability of Filter B is given in Figure 12. Over the interval 3900 to 6550A, the rejection is better than eight orders of magnitude. Outside of a "leak" from 4300 to 5000A, the rejection is greater then eleven orders of magnitude. A future task objective is to improve the rejection in the 4300-5000A range from eight orders of magnitude to at least eleven.

The transmittance of Filter AB is shown on a logarithmic scale in Figure 13, and on a linear scale in Figure 14. The peak transmittance is about 25 percent, and the transmittance band runs from 2450 to 3000A.

The rejection of Filter AB in the UV is better than four orders of magnitude below 3400A [see Figure 13], increasing to better than twelve orders of magnitude at 4000A. As seen from Figure 15, there is a "leak" extending from 4200 to 5100A, but nowhere is the rejection less than 8.5 orders of magnitude. For this filter there is no leak above 6500A, in contrast to that of Filter B. The rejection above 5600A through the infrared is better than five orders of magnitude.

Imaging Performance

The resolution (effect upon imaging quality) of the elements of the filter set was measured using Test Bench Layout II.

Preliminary tests showed the resolution of the bench system without any filter in the test position to be approximately 50 line-pairs per mm (test target Group 5, Element 5, identifying resolution pattern element 5-5). It is probable that the system resolution is inherently much better, but this was sufficient for our Phase I objectives and limited time did not allow us to obtain measurements confirming a higher level of inherent resolution capability.
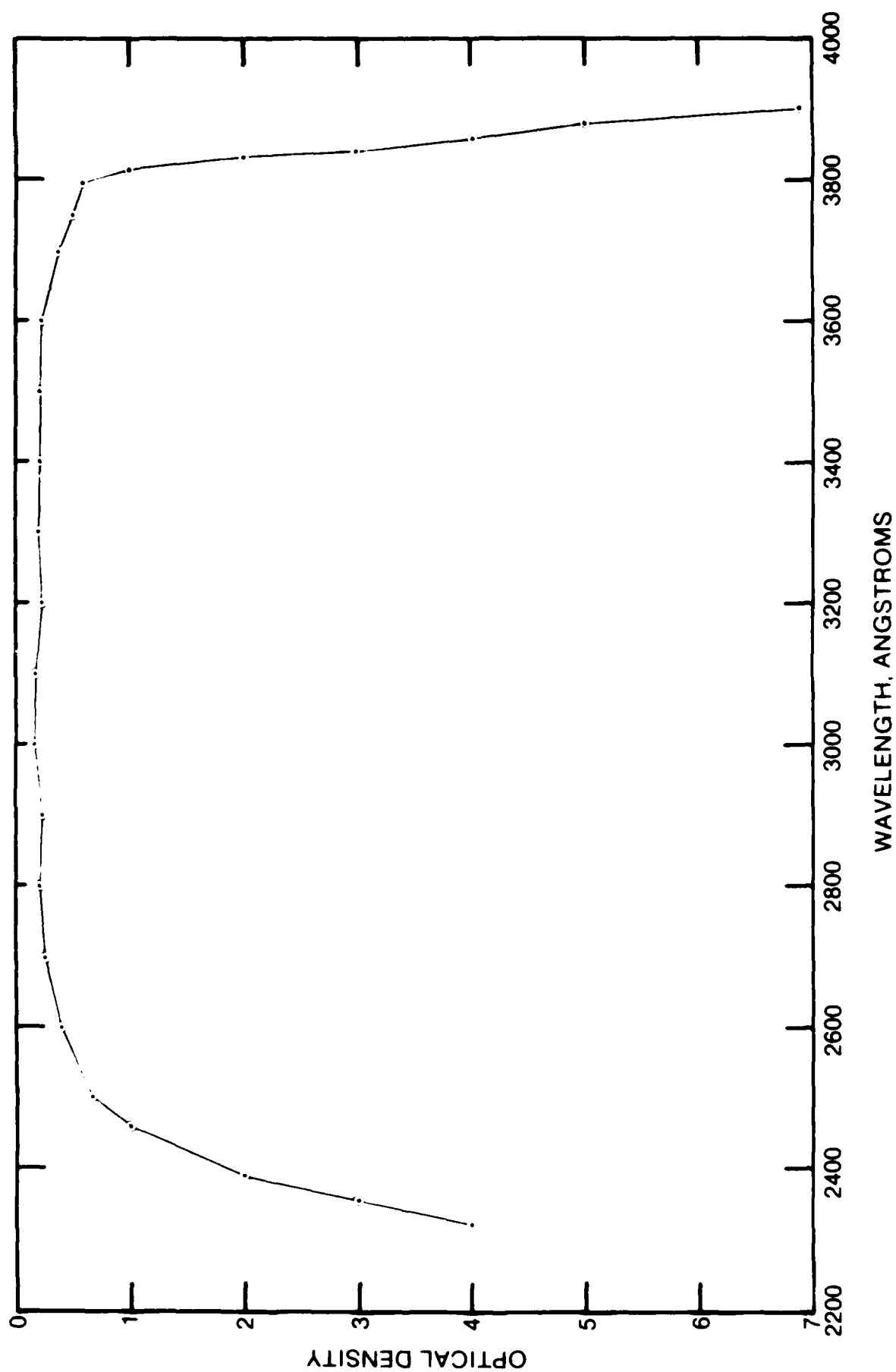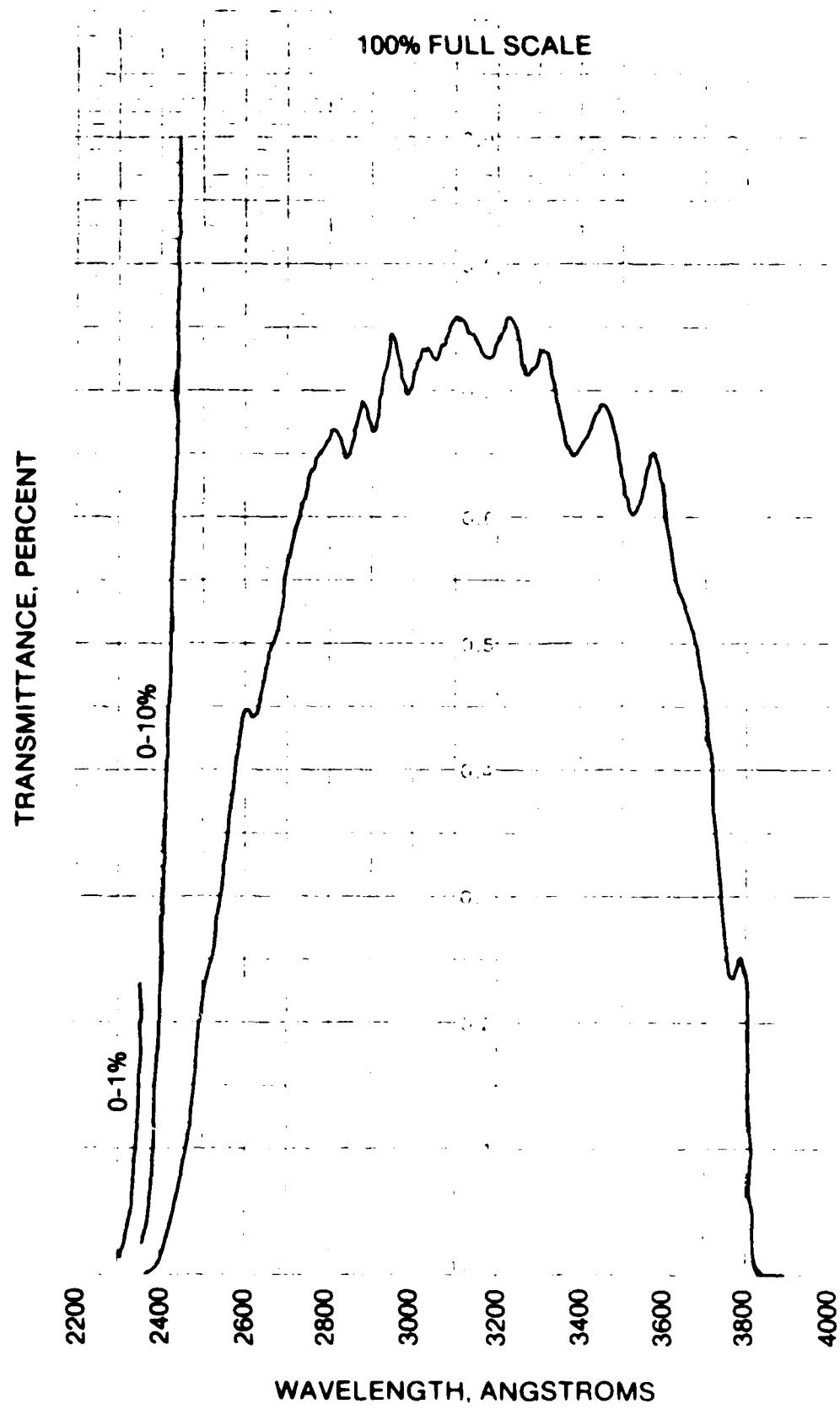
Figure 10. Spectral Transmittance - Filter B

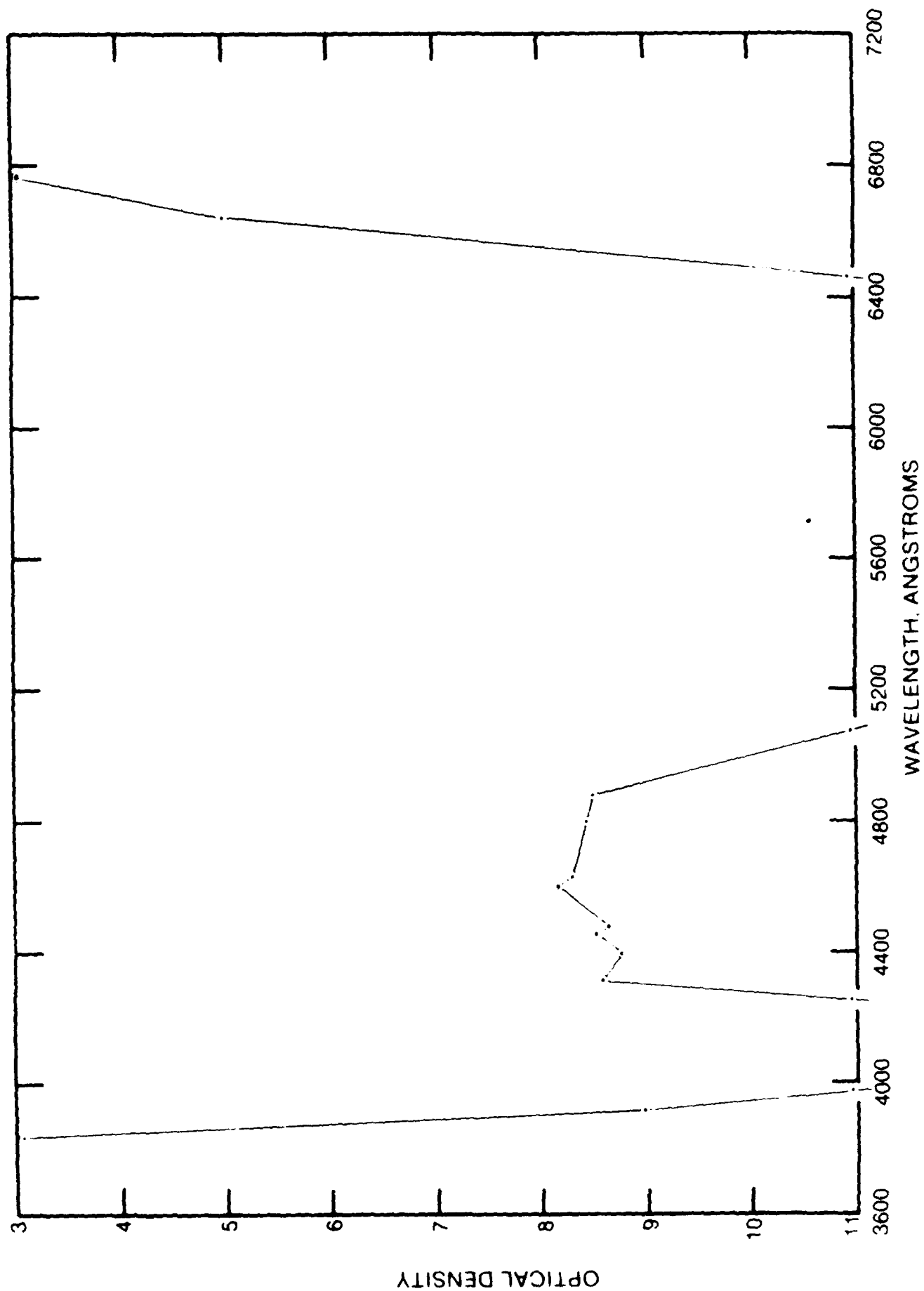Figure 11.   Spectral Transmittance - Filter B
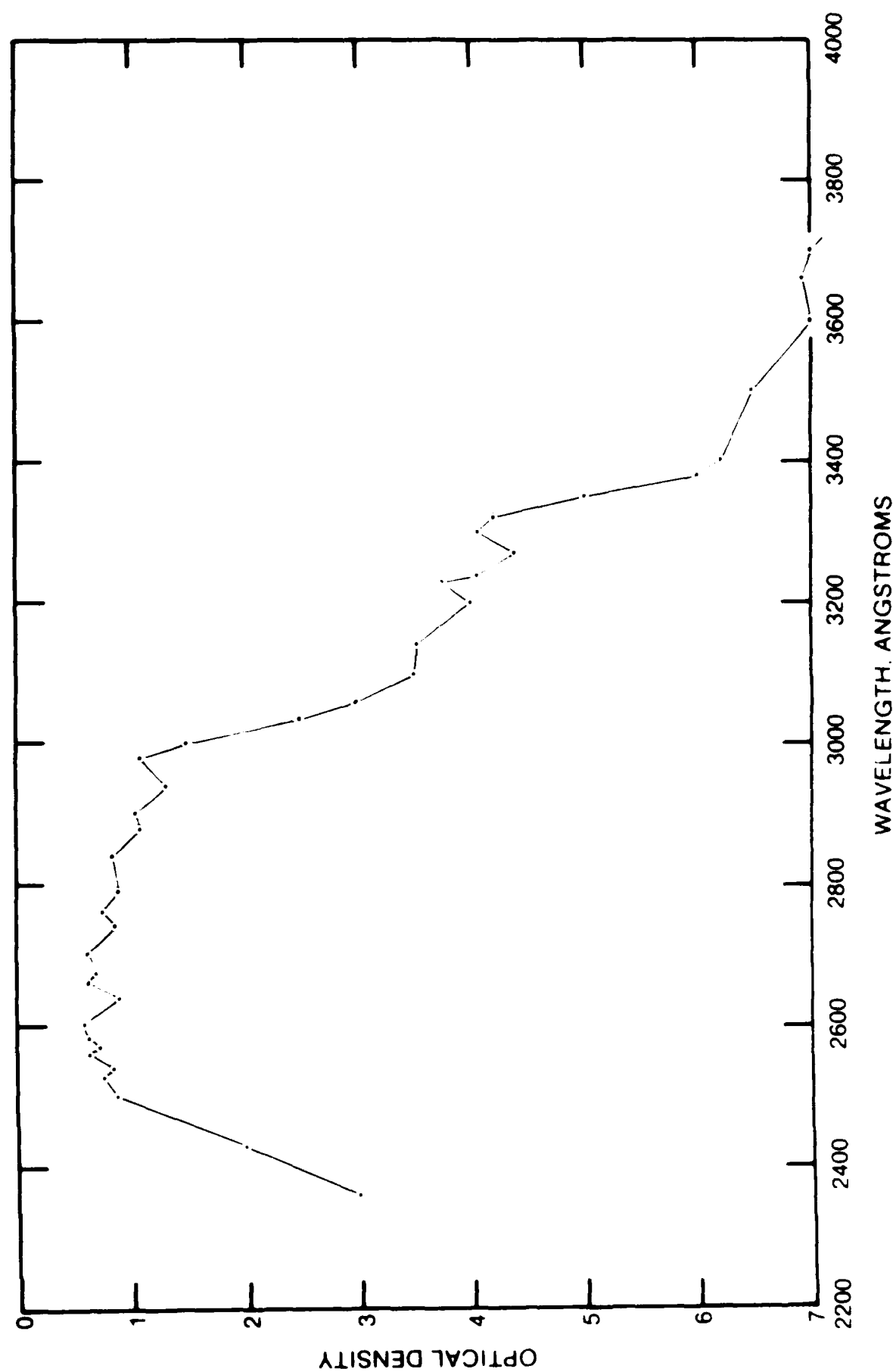
Figure 12. Spectral Rejection - Filter B

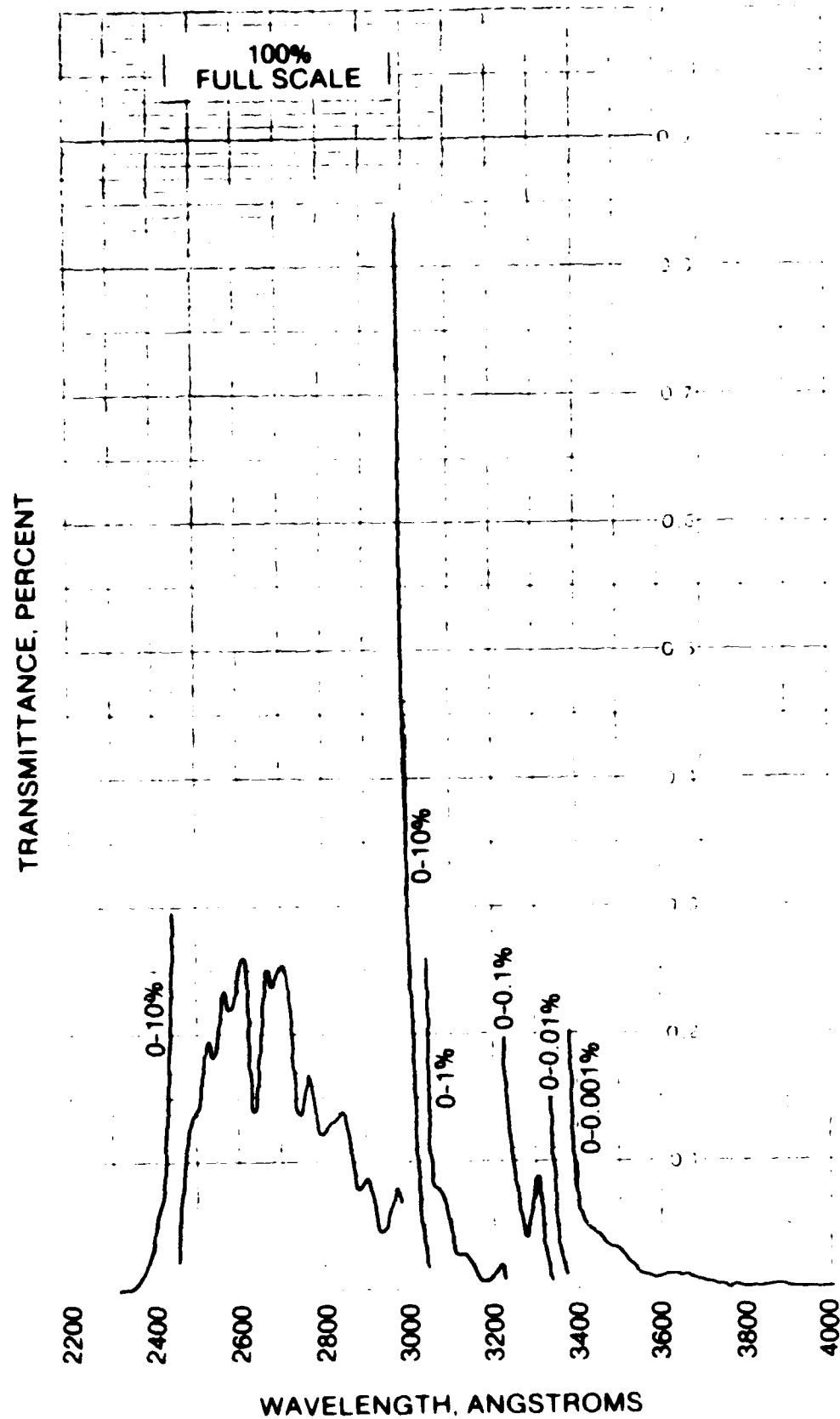Figure 13. Spectral Transmittance - Filter AB
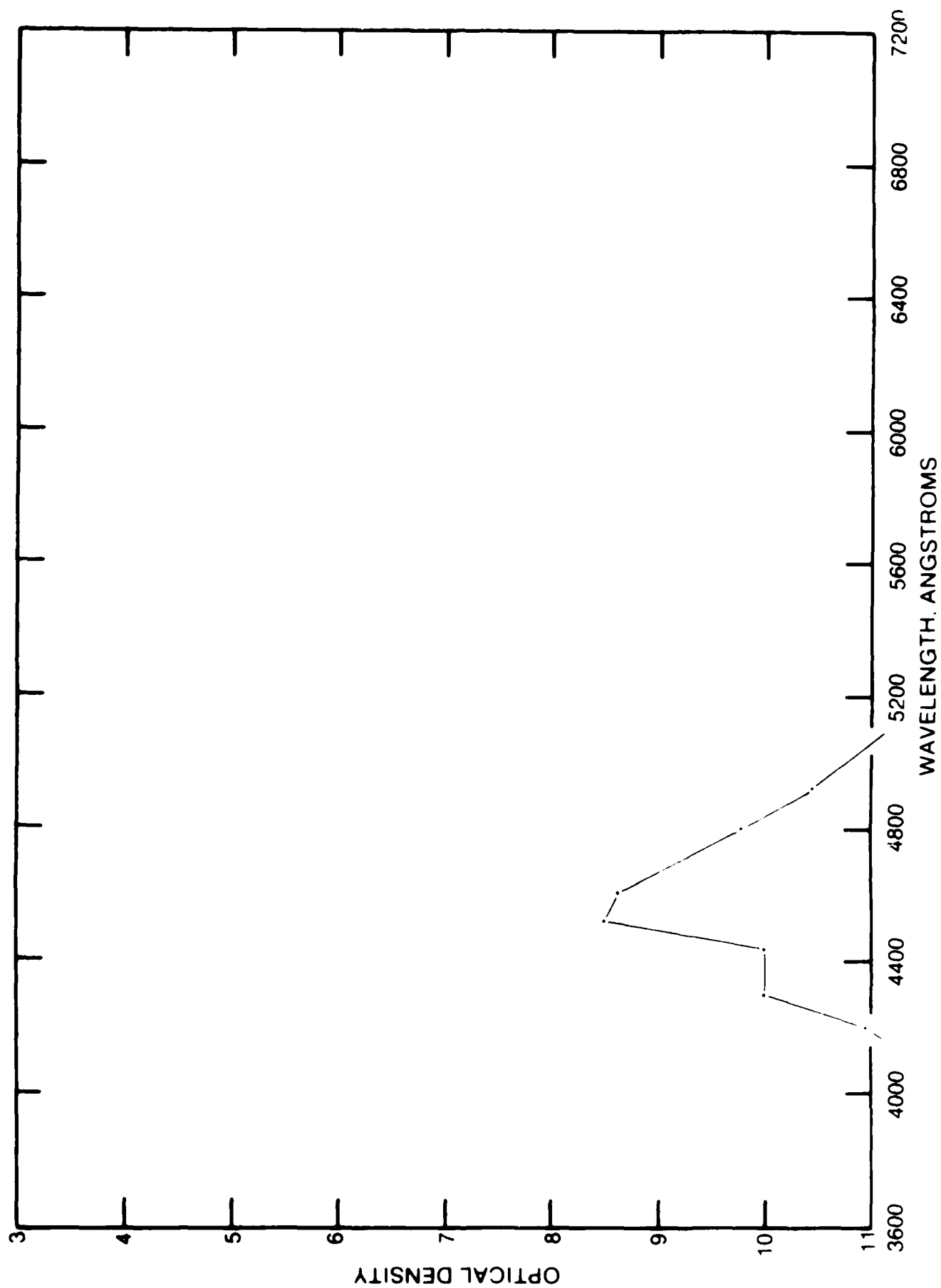
Figure 14. Spectral Transmittance - Filter AB

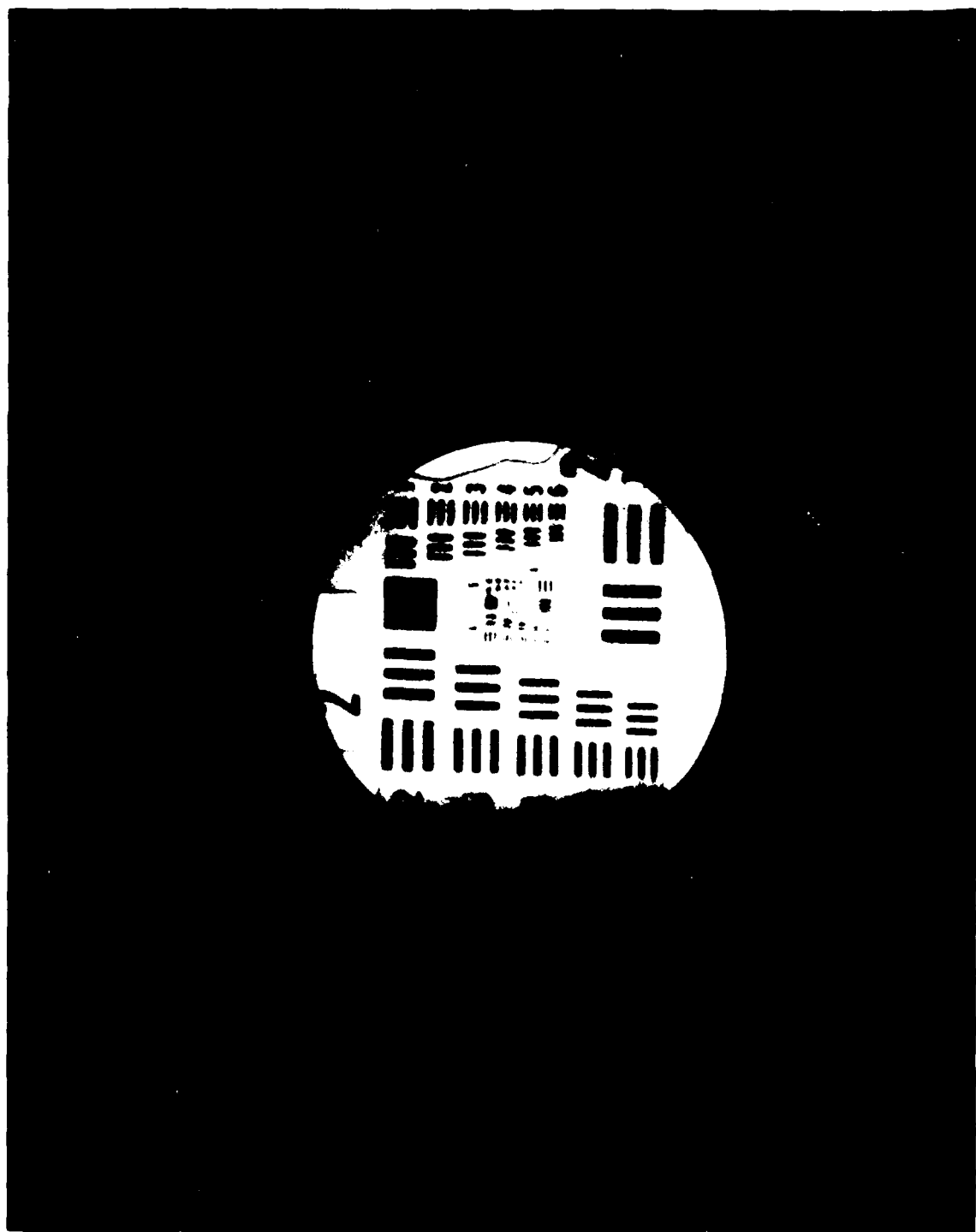Figure 15.   Spectral Rejection – Filter AB

Figure 16. Typical Test Image of Resolution Target - Filter B

With Filter B interposed in the test bench, and the system refocused, we obtained several polaroid prints with different focus adjustments and exposure settings. One of the best resolved of these is shown as an example in Figure 16; this photo shows that test target element 5-4 is resolved, corresponding to 45 line-pairs per mm.

All filters in the set were similarly tested. The results are summarized in Table I.

TABLE I

Summary of Resolution Measurements

Test Bench Configuration	Target Resolved	Image Resolution	Element Resolution
with no filter	5-5	50 1-p/mm	50+ (60 est.)
with Filter B	5-4	45	68
with Filter AB	5-1	32	38
with Filter Q	4-6	29	33
Film			94

In Table I the second column shows the finest element of the USAF test target image that could just be resolved in the best polaroid image photograph using that filter. The corresponding resolution value [see the table in Figure 5] is given in the third column. This is a measure of image definition capability of the total test bench system with the filter in place. The results reported in the table show the best focussed image (best resolved target image) that we obtained, but this does not necessarily mean that this is the best resolution that could be obtained.* As mentioned in Section 6 (Test Methodology), the test bench was assembled to get sufficient data to ascertain accomplishment of the Phase I objectives for resolution performance, better than 15 line-pairs per mm. In our efforts to see how much better than minimum acceptable resolution has been achieved we have been somewhat impeded by the temporary nature of the test bench, the absence of fine-adjustment capability, instabilities in system alignment, the absence of a screen that could be directly observed, and the tediousness of making multiple polaroid prints with small focus adjustments between each film exposure.

The most difficult aspect has been the absence of a screen that could be directly observed for best focus while various adjustments are made, and in a continuation of the program this is an item that deserves attention.

The system resolution capability tabulated in the third column, "Image Resolution", represents the combination of the contribution of each of the elements in the total optical system to image quality. Conceptually, it is probably easier to consider each element not in terms of its contribution to image quality, but rather the extent to which it falls short of the ideal, the extent to which it contributes to degrading the imaging quality of the system. Now the best quantitative representation (estimate) of the way the individual component capabilities combine is a reciprocal squared summation [see Reference 3].

The total system imaging capability (resolution) can therefore be regarded as the resolution capability of the system without the filter, and the resolution of the filter alone, combined in a reciprocal squared summation. If we make the assumption that the test system without a filter has a resolution capability of 60 line-pairs per mm (which is a reasonable estimate and consistent with earlier measurements before the press camera and filmpack were employed to obtain recorded images), then we can calculate from the measured system resolution with a filter in place what the resolution capability of the filter element alone should be. This is obviously an estimate, and depends upon the accuracy of our input data and assumptions, but we think it is not too bad. The results of such a calculation are given in the fourth column of the table, headed "Element Resolution". It should be recognized that the poorer the resolution assumed for the test system without the filter, the better appearing will be the values in column four for the resolution capability of the filter elements alone. Conservatively therefore, one should lean in the direction of an optimistic value for the resolution of the test system without the filter. We believe we have made a good choice.

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*NOTE: We know that on the day that all of these particular data were taken our ability to obtain an optimally focussed image grew poorer as the day progressed. Furthermore, earlier measurements showed the image quality using the fused silica spacer, Filter Q, to be barely perceptively poorer than for the system with no filter. From the physical construction of Filter AB, there is no reason to expect its image capability to be significantly different from that of Filter B. Consequently, the tabulated data represent a lower bound to performance and, at least for Filter AB and Filter Q, the filters are probably better than the measured data indicate. An improved test bench would be capable of producing more accurate measurements.

8. Conclusions

1. The objectives of Phase I of this research program have been accomplished.

2. A representative set of optical filters suitable for use in obtaining high-definition ultraviolet images with a telescopic camera has been designed.

3. The designs have been realized by fabricating a set of physical filters.

4. The resulting filters have been thoroughly tested. The test results show that the performance specifications have been met and exceeded.

5. The imaging quality of the filter set is sufficiently good that there should be no noticeable degradation in the imaging performance of the camera system in which they are intended to be used, which has been estimated to be 15 to 20 line-pairs per mm.

6. Based on the results of the resolution measurements, the inherent image definition capability of the filters themselves is estimated to be better than 40 line-pairs per mm.

7. The successful accomplishment of the Phase I objectives has demonstrated the feasibility of developing a more general design and manufacturing capability that will provide high-resolution ultraviolet filters readily and reliably.

8. A Phase II program in continuation of this research has been justified and should be undertaken.

9. Recommendations

1. The development of a design and manufacturing technology that can produce high resolution (high imaging quality) ultraviolet filters, as initiated by this Phase I Innovative Research project, should be further pursued in greater depth by means of a Phase II follow-on program.

2. The Phase II program should include at least:

    (1). Fundamental work on improving computer design methods and on selection of materials.

    (2). Development of computer-assisted designs for specific filter application classes.

    (3). Experimental work with alternative deposition technologies to achieve better filter performance, both spectrally and in imaging capability.

    (4). Exploration of modifications to deposition equipment to facilitate fabricating better filters more reproducibly and more cost-effectively.

    (5). More detailed investigation of deposition parameters, background gasses, and other process characteristics.

    (6). Further analysis of filter structure, including substrate materials and film positioning.

    (7). Study of the geometrical optics of representative camera systems, the contribution of filters to system aberrations, and the impact of system imaging requirements upon filter design.

    (8). Development of a cost-effective test bench design capable of adequate resolution measurement and efficient operation. Consideration should be given to test target design, elimination of secondary images, design of imaging optics for testing with relatively short target-to-image distances (within laboratory space limitations), and efficient methods of image recording.

    (9). Consideration of production technology requirements, so that implementation of production in Phase III can be confidently undertaken with respectable yields and economy of production.

3. The Phase II program should encompass the ability to produce filters for expected imaging requirements in the ultraviolet, extending down into the vacuum ultraviolet (VUV) to probably 1200A (for H 1216, Lyman-alpha), and including both narrow-band (100 to 300A) and wide-band filters as well as short-pass filters. Desirable characteristics to be improved upon include deeper rejection, sharper transition slopes between transmission and rejection regions, and higher transmittance. Attention should also be given to better cataloging the characteristics of typical imaging systems, and their anticipated filter requirements.

4. The pursuit of Phase II should be accompanied by a sensitivity to other applications for the technology. The availability of an innovative technology may well lead to the identification of existing problems to which the technology is applicable, and create new perceptions of need and demand. The recognition of potential applications is a responsibility that should be embraced in the execution of Phase II. It is to be expected that there will be numerous applications in the defense establishment, both classified and unclassified, as well as in other government and in private technological institutions. Recognition and definition of needs is a necessary prerequisite to making high-resolution ultraviolet filters available to military, aerospace, scientific and commercial users.

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